Do the Infrared Emission Features Need Ultraviolet Excitation[1] ?

K.I. Uchida[2,3], K. Sellgren[2], and M. Werner[4]

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ABSTRACT

We present the results of imaging spectroscopy of the reflection nebula vdB 133, obtained with the infrared camera and circular variable filter wheel on the Infrared Space Observatory (ISO). Our observations reveal the infrared emission features (IEFs), at 6.2, 7.7, 8.6, 11.3, and 12.7 μm, and associated 5 – 15 μm continuum emission. The stellar system illuminating vdB 133 has the lowest ratio of ultraviolet (shortward of 0.4 μm) to total flux of any stars demonstrated to date to excite the IEFs and associated continuum emission from adjacent *interstellar* dust, as opposed to circumstellar dust. The low fraction of UV flux from this system poses a problem for existing models for the emission mechanism and emitting material, which all require substantial UV radiation for the excitation of the IEFs and associated continuum.

Subject headings: infrared: ISM: lines and bands — dust, extinction — ISM: molecules — reflection nebulae — ISM: individual (vdB 133) — stars: individual (HD 195593)

1. Introduction

The Infrared Emission Features (IEFs), at 3.3, 6.2, 7.7, 8.6, 11.3, and 12.7 μm, appear in spectra of our own and other galaxies, wherever the interstellar medium is exposed to optical-ultraviolet (UV) radiation (see reviews by Puget & Léger 1989 and Allamandola, Tielens, & Barker 1989). Proposed identifications for the IEFs include polycyclic aromatic hydrocarbon (PAH) molecules (Léger & Puget 1984; Allamandola, Tielens, & Barker 1985) and grains composed of more amorphous aromatic hydrocarbons (Sakata et al. 1984, 1987; Blanco, Bussoletti, & Colangeli 1988; Duley 1988; Papoular et al. 1989).

In this letter we present the detection of interstellar IEFs in the 5 – 15 μm spectrum of vdB 133, where the interstellar medium is excited by a stellar system emitting relatively little UV flux shortward of 0.4 μm. The main illuminating sources of the reflection nebulae vdB 133 are the stars HD 195593A and B, with spectral types F5 Iab (T_{eff} = 6,500 K) and B7 II (T_{eff} = 12,700 K), respectively. The spectrum presented here is the first result from a search for IEFs toward reflection nebulae illuminated by relatively cool stars, made possible by the unprecedented sensitivity of the cryogenically cooled Infrared Space Observatory (ISO) satellite (Kessler et al. 1996) to low surface brightness mid-infrared emission. Our goal is to test theoretical predictions of how the IEFs depend on optical-UV illumination.

2. Observations

We obtained observations of vdB 133, with ISO's mid-infrared camera, ISOCAM (C. Cesarsky et al. 1996), and the circular variable filter (CVF), in 1997 April. We used the 6″/pixel scale, giving a total angular coverage of 3.′2 by the 32×32 pixel array. The CVF spectral resolution was $\lambda/\Delta\lambda = 40$ (ISOCAM Team 1996). We performed a complete CVF scan from 5.1 to 15.1 μm on the nebula, followed immediately by a complete CVF scan on a nearby sky position. Each CVF scan contained two overlapping spectral sequences: one sequence of images from 5.1 to 9.4 μm, with a CVF wavelength increment of 0.05 – 0.06 μm between images; and one sequence from 9.3 to 15.1 μm, with images obtained every 0.10 – 0.11 μm. These wavelength increments correspond to one CVF step between each image, and sample the spectrum 2 – 4 times per CVF spectral resolution element. We obtained two independent scans, one performed in increasing wavelength, and another performed in decreasing wavelength. Our total on-source integration time was 46 s for each CVF position.

Our first step in the reduction of these images was to remove cosmic ray hits, followed by dark current subtraction. We then corrected for the flux-dependent transient response of the detector using a model developed at the Institut d'Astrophysique (Siebenmorgen et al. 1996), as described by Abergel et al. (1996). Our final data reduction steps were subtraction of the sky images, application of a flat field correction, and averaging the up and down scans. More detail on each of these steps will be given in a subsequent paper (Uchida, Sellgren, & Werner 1997).

3. Results

3.1. The Infrared Emission Features

We observe extended infrared emission $\sim$100″ northeast of the illuminating stars in vdB 133. This emission is spatially and spectrally dis-

tinct from the diffuse emission we observe near HD 195593A, due to stray light scattered from the CVF filter. We will present spectral images and a discussion of the nebular spatial structure in a second paper (Uchida et al. 1997).

We present the complete CVF spectrum of the vdB 133 nebular peak, after sky subtraction, in Figure 1.

Our spectrum clearly shows the IEFs at 6.2, 7.7, 8.7, 11.3, and 12.7 μm in vdB 133. We also observe continuum emission from vdB 133 throughout the 5 – 15 μm region, as well as the broad 6 – 9 μm emission "bump" and the 11 – 13 μm emission plateau. All of these spectral components are characteristic of other interstellar medium sources illuminated by much hotter stars (e.g., NGC 7023, $T_{\mathrm{eff}} = 18,000$ K; see review by Allamandola et al. 1989).
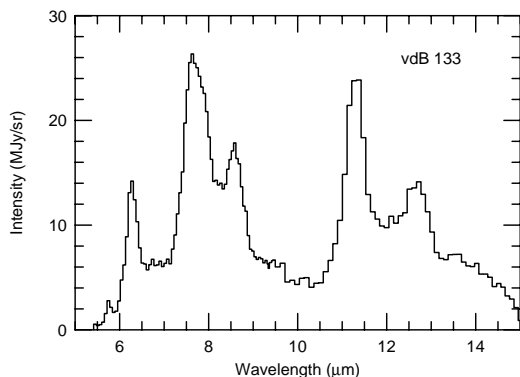
3.2. HD 195593A and B

HD 195593A (F5 Iab) has two companions, B and C. The Tycho catalog (ESA 1997) reports a V magnitude difference of 2.6 between HD 195593A and B, based on CCD photometry with the Hipparcus satellite. Earlier visual estimates for the magnitude difference

between HD 195593A and HD 195593B range from 3.5 to 6 magnitudes (Aitken 1932; Baize 1957; Pettit 1958). Little is known about HD 195593C besides its visual magnitude (Kuiper 1961).

We have classified HD 195593B as B6 – B8, from a high resolution optical spectrum of HD 195593B kindly obtained for us by C. Barnbaum with the Hamilton echelle spectrograph on the 3m Shane telescope. We have used the B and V photometry of the Tycho Catalogue (ESA 1997) for HD 195593A and B, together with the intrinsic colors of these stars (Johnson 1966), to derive reddenings of $E(B - V) = 0.69$ and 0.83 ± 0.10, respectively. Because HD 195593 A and B are only separated by 2″, and their reddenings are the same within the uncertainties, they are likely to be physically associated.

Humphreys (1978) and Garmany & Stencel (1992) conclude that HD 195593A is a member of the Cyg OB1 association, which has a distance modulus of 10.9 ± 0.4. This, together with the extinction, implies absolute magnitudes of $M_V = -6.6 \pm 0.4$ for HD 195593A and $M_V = -4.0 \pm 0.4$ for HD 195593B. The luminosity class for HD 195593B is II to Ib based on its absolute magnitude; the rotational broadening of its spectral lines in the optical spectrum argue against a Ib classification (Slettebak 1997). We adopt a spectral classification of B7II ($T_{\mathrm{eff}} = 12,700$ K) for HD 195593B.

We have considered the possibility that the other earlier type stars in the Cyg OB1 association are providing the necessary UV radiation to excite the infrared emission we observe, but have found their contribution to be negligible. HD 195593 lies at the outskirts of Cyg OB1, at a projected distance of ∼2.8 degrees or ∼70 pc from the association cen-

ter (Garmany & Stencel 1992). We have used the bolometric magnitudes and projected positions on the sky for luminous stars in Cyg OB1 (Humphreys & McElroy 1984; Garmany & Stencel 1992) to estimate the sum of the fluxes from individual Cyg OB1 stars incident on vdB 133. We find that the bolometric flux from other Cyg OB1 members is only 2–3% of the total flux from HD 195593 incident on the nebular peak in vdB 133. We also have examined our unpublished H and K images of vdB 133, and find no evidence for any highly reddened, luminous stars near HD 195593 which might be an alternate source of excitation.

4. Discussion

4.1. Interstellar and Circumstellar IEFs

Recent reviews (Geballe 1996; Tokunaga 1996) emphasize the spectral differences between interstellar IEFs and circumstellar IEFs. Class A sources show strong, relatively narrow, emission features at 3.3, 6.2, 7.7, 8.7, 11.3 and 12.7 μm, while Class B sources instead have narrow emission features at 3.3, 6.2, and 6.9 μm and broad emission bumps at 3.4, 8 and 12 μm (Geballe 1996; Tokunaga 1996). IEFs from interstellar dust are always of Class A type as demonstrated by many spectra of individual H II regions, reflection nebulae, and the diffuse interstellar medium in our own and other galaxies. Carbon-rich planetary nebulae also have Class A spectra. Class B spectra, by contrast, appear only in circumstellar dust. Most Class B sources are F and G stars in transition between the AGB and the planetary nebulae phase.

The spectrum of interstellar dust in vdB 133 is clearly a Class A IEF emission spectrum (Figure 1). The origin of the spectral differences and inferred UV absorption character-istics between Class A and Class B sources is currently debated (Geballe 1996; Tokunaga 1996). It may be due to differences in composition, size, or excitation of the IEF carriers.

IEFs from *interstellar* dust is usually associated with UV radiation, yet the central stars of vdB 133 provide very little UV radiation. The HD 195593 pair emits only 21% of its total luminosity shortward of 0.4 μm, as determined from atmospheric models described by Buser & Kurucz (1992). We use the models with parameters closest matching those of the stars': $T_{\rm eff} = 6,500$ K and $\log g = 2.0$ for stellar component A and $T_{\rm eff} = 13,000$ K and $\log g = 3.5$ for component B. The previous record holder for lowest ratio of UV to total luminosity for stars exciting interstellar IEFs was BD +30 549 (B8V; $T_{\rm eff} = 11,000$ K), which illuminates the visual reflection nebula NGC 1333 (Whittet et al. 1983; Sellgren, Werner, & Allamandola 1996). BD +30 549 emits 55% of its total luminosity shortward of 0.4 μm (using the atmospheric models with $T_{\rm eff} = 11,000$ K and $\log g = 4.0$), more than double that of the HD 195593 system.

Other IEF sources have been observed with low ratios of UV to total luminosity, but only in *circumstellar* dust. IEFs has been previously detected in circumstellar dust surrounding F, G, K, and perhaps M stars (Kwok et al. 1989; Buss et al. 1990; Buss et al. 1993; Sylvester et al. 1994; Kwok et al. 1995; Coulson & Walther 1995; Skinner et al. 1995; Justtanont et al. 1996). These cool circumstellar sources are usually observed to be Class B sources whenever sufficient signal-to-noise and wavelength coverage are available to make the distinction between Class A and Class B.

The detection of IEFs in vdB 133 is significant because its central stars, HD 195593A

and B, have a lower combined ratio of UV to total luminosity than any other star known to excite IEFs by illuminating *interstellar* rather than circumstellar dust. The interstellar nature of the dust in vdB 133 is underscored by its Class A spectrum.

4.2. Excitation of the IEFs

The proposed emission mechanisms for the interstellar IEFs and their associated continuum all predict that the emission due to tiny particles should drop precipitously in the absence of UV photons. These models include stochastic heating by single UV photons of tiny grains (Sellgren 1984), UV-pumped fluorescence of PAH molecules (Allamandola et al. 1985), and stochastic heating by single UV photons of thermally isolated clusters within large grains (Duley 1988). UV photons are essential for PAH fluorescence, because PAH molecules only absorb strongly in the UV. Aromatic hydrocarbon grains absorb over a wider range of wavelengths, but UV photons are most effective at heating both tiny grains and thermal islands within large grains. Reflection nebulae illuminated by cool stars, with little or no UV, provide ideal interstellar "laboratories" for stringently testing different excitation mechanisms and carrier materials for the IEFs.

The observations of Sellgren, Luan, & Werner (1990), however, contradict the strong UV dependence of tiny particle emission predicted by both stochastic heating and UV fluorescence models. Sellgren et al. (1990) have examined IRAS observations of reflection nebulae illuminated by stars with different values of T_{eff}. Surprisingly, they find that tiny particle emission traced by the IRAS 12 μm band is a constant fraction of the total infrared emission in reflection nebulae illuminated by stars with T_{eff} = 5,000 – 21,000 K. The ratio of UV luminosity to total luminosity ranges from 0.07 to 0.90 for this range of stellar temperature. Sellgren et al. (1990) conclude that the carriers of the IRAS 12 μm emission have to absorb over a wide range of wavelengths, both visible and ultraviolet, in order to emit as much energy as observed.

The broad bandpass of the IRAS 12 μm filter, however, leaves open the question of whether reflection nebulae illuminated by cooler stars have the same spectral mix of IEFs, broad spectral features, and continuum that characterizes dust near hotter stars. Allamandola et al. (1989) and Bregman et al. (1989) identify the IEFs with PAH molecules, but attribute the broad spectral structure at 6 – 9 μm and 11 – 13 μm to PAH clusters and amorphous carbon grains. Both laboratory spectra, and observations of differences in spatial distributions of different IEFs, the continuum, and the broad plateau features, provide compelling evidence for a distinction between the emitting materials for different spectral components. Such a composition difference may also result in differences in excitation.

Our spectrum of vdB 133, however, shows no difference from the spectra of other interstellar medium sources excited by much hotter stars. We quantify the relative amount of IEF emission, compared to broader spectral structure and continuum emission, by convolving our ISO spectrum with the 12 μm IRAS filter bandpass. We find that 23% of the 12 μm IRAS flux is due to IEFs in vdB 133. We derive a very similar value, 21%, from the ISO spectrum of the reflection nebula NGC 7023 (D. Cesarsky et al. 1996), illuminated by a B3e star (T_{eff} = 18,000 K).

HD 195593B, by itself, is unable to account

for the IEFs we observe toward vdB 133. The observations of Sellgren et al. (1990) show that B6–8 stars have an average ratio of 0.24 for the ratio of the energy emitted within the 12 μm IRAS band, $\Delta\nu I_\nu(12\ \mu\text{m})$, to the total energy emitted by dust at far-infrared wavelengths, $I_{bol}(\text{FIR})$. Only 17% of the bolometric luminosity *emitted* by the central stars in vdB 133 is due to the hotter star, HD 195593B. After convolving the interstellar extinction curve with the energy distributions of both stars, we find that only 22% of the starlight *absorbed* by dust in vdB 133 is due to HD 195593B. If all of the excitation of the IEFs in vdB 133 comes from HD 195593B, while the far-infrared emission is excited by both HD 195593A and HD 195593B, then we expect $\Delta\nu I_\nu(12\ \mu\text{m})/I_{bol}(\text{FIR})$ to be about 22% of 0.24, or 0.05. Sellgren et al. (1990) instead observe $\Delta\nu I_\nu(12\ \mu\text{m})/I_{bol}(\text{FIR})$ to be 0.19 for vdB 133. This value is a factor of four larger than can be provided by HD 195593B alone, and shows that much of the IEF excitation in vdB 133 is due to the F5Iab star, HD 195593A.

The reflection nebulae vdB 133 and NGC 7023 have similar infrared properties but very different stellar energy distributions for the exciting sources of each. Table 1 quantifies this comparison. The fraction of the IRAS 12 μm band due to the narrow infrared emission features (col. 2) is essentially identical for the two sources. The IRAS 12 μm emission is also a similar fraction of the total energy absorbed from starlight and re-radiated by dust for these nebulae, as shown by $\Delta\nu I_\nu(12\ \mu\text{m})/I_{bol}(\text{FIR})$ (Sellgren et al. 1990) in column 3. Yet only a small fraction of the starlight exciting vdB 133 is emitted shortward of 400 nm, while virtually all the starlight exciting NGC 7023 is shortward of 400 nm (col. 4). The

similarity in infrared spectra together with the marked difference in stellar excitation in vdB 133 and NGC 7023 lead us to conclude that the IEF carriers absorb over a wide range of wavelengths, both visible and ultraviolet.

4.3. Future Directions

Our detection of IEFs in vdB 133, where interstellar dust is illuminated by a stellar system with relatively little UV radiation, poses a challenge to current models for the IEF carriers and emission mechanisms. In an upcoming paper, we will present a quantitative study of the laboratory absorption curves of different proposed materials for the IEFs, convolved with the energy distributions of the stars illuminating vdB 133 (Uchida et al. 1997). We are also using ISO to obtain CVF scans toward other reflection nebulae illuminated by stars with $T_{\text{eff}} = 3,600 - 19,000$ K, as further tests of proposed emission mechanisms and materials for the IEFs.

TABLE 1
NEBULA EMISSION CHARACTERISTICS

Star	$\dfrac{\text{F(IEF)}}{\text{F(12 }\mu\text{m IRAS)}}$	$\dfrac{\Delta\nu I_\nu(12\ \mu\text{m IRAS})}{I_{\text{bol}}(\text{FIR})}$	$\dfrac{F_*(\lambda < 400\ \text{nm})}{F_*(\text{Total})}$
vdB 133	0.23	0.19	0.21
NGC 7023	0.21	0.09	0.86

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Fig. 1.— $5.1 – 15.1$ μm spectrum of the reflection nebula vdB 133. The stars illuminating vdB 133 have the lowest ratio of ultraviolet to total flux of any stars discovered to date to excite the IEFs and associated continuum emission from interstellar dust. The spectrum was obtained with the camera on the Infrared Space Observatory (ISO) and a circular variable filter wheel ($\lambda/\Delta\lambda = 40$). The spectrum has been corrected for the flux-dependent responsivity of the detectors, and the spectrum of a nearby reference position subtracted.